Energy, Mines and Resources Canada

Énergie, Mines et Ressources Canada

CANMET

Canada Centre for Mineral and Energy Technology

Centre canadien de la technologie des minéraux et de l'énergie

Metals Technology Laboratories

Laboratoires de la technologie des métaux

Canada

METALS TECHNOLOGY LABORATORIES

91-04572/

OVERVIEW OF WEAR RESISTANT MATERIALS IN THE CANADIAN RESOURCE INDUSTRY

K.C. WANG

MTL 90-33(TR)

MICROMEDIA

14 pp

CANMET

METALS TECHNOLOGY LABORATORIES
REPORT MTL 90-33(TR)

OVERVIEW OF WEAR RESISTANT MATERIALS IN THE CANADIAN RESOURCE INDUSTRY

by

K.C. Wang

INTRODUCTION

Wear-resistant materials are used extensively throughout the mining and mineral processing systems such as drilling, boring, digging, haulage, crushing, grinding, slurry systems etc as listed in Table 1 (1). Materials selected for each particular application depends not only on the intrinsic properties of the material itself but largely on the tribological system. An ideal wear-resistant material should possess hardness to resist indentation and scratching, toughness to resist crack initiation and propagation, inertness to resist corrosion, formability and weldability to ease application and replacement, availability and economy to reduce cost. Since most of the requirements are mutually exclusive, materials can only be selected based on a specific application. Wear materials can be categorized into hard materials such as diamond, ceramics and carbides metallic materials which includes quenched and tempered steels, manganese steels, white irons and hard-facing materials; and plastics (1,2). The critical areas which can benefit Canadian industry most and lie within CANMET's capabilities are examined in this report.

LABORATOIRES DE LA TECHNOLOGIE DES MÉTAUX
RAPPORT MTL 90-33(TR)

EXAMEN DES MATÉRIAUX RÉSISTANTS À L'USURE QU'UTILISE L'INDUSTRIE CANADIENNE DES RESSOURCES

par

K.C. Wang

INTRODUCTION

Les matériaux résistants à l'usure sont largement utilisés par l'industrie minière et du traitement des minéraux, notamment pour le forrage, le sondage, le creusage, le roulage, le broyage, le meulage, les systèmes de bouillie, etc. [voir le tableau 1 (1)]. Le choix des matériaux propres à chaque application dépend non seulement des propriétés spécifiques du matériau, mais aussi du système triboligique. L'idéal serait de posséder un matériau résistant qui présenterait à la fois les caractéristiques suivantes: dureté, pour résister à la pénétration et au rayage, ténacité, pour résister à la formation et à la propagation de fissures, inactivité chimique, pour résister à la corrosion, formabilitè et soudabilité, pour faciliter l'application et le remplacement, disponibilité et écomonomie, pour réduire les coûts. Puisque la plupart des exigences sont incompatibles, le choix des matériaux ne peut se faire qu'en fonction d'une application précise. Les matériaux résistants à l'usure se classent en trois catégories: matériaux durs comme le diamant; céramiques et carbures métalliques, y compris les aciers trempés et revenus, les aciers au manganèse, les fontes blanches et les matériaux de rechargement en dur; et plastiques (1,2). Le rapport passe en revue les domaines critiques qui profiteront le plus à l'industrie canadienne et dans lesquels CANMET est en mesure de réaliser des études.

TRIBOLOGICAL SYSTEMS

A typical systems approach in materials selection is shown in Tables 2 and 3 (3). For materials used in the resource industries, abrasive wear is dominant. Factors influencing abrasive wear are listed in Table 4 (1). A simplified model to describe abrasive wear is

$$W = \frac{1}{V} = \frac{\pi}{\tan\theta}\,\frac{H}{PL}$$

where: W = wear resistance
V = wear volume
P = normal load
L = sliding distance
H = hardness of abraded material
θ = attack angle

That is, if everything else is held constant, the wear resistance is directly proportional to the hardness of the abraded material.

The material with the highest hardness is diamond, which has been used in expensive down-hole drilling and cutting tools. Ceramics, with high hardness but also high brittleness, are used in applications where impact is not a major concern (carbides with higher hardness then metallic materials yet with moderate toughness are used quite widely). The bulk materials used in the resource industries are metals which have a range of hardness and toughness. In environments where impact is dominant, plastics are also used to absorb the impact energy, and they have a reasonable life.

HARD MATERIALS

Diamond, cubic boron nitride, ceramics and refractory carbides lie in this group of materials. They all have high hardness and low toughness. Their properties are shown in Tables 5 to 8 (1,4). In abrasive wear, the wear rate decreases sharply when the ratio between the hardness of the abraded material, H, over the abrasive, Ha, increases above 0.6 as shown in Fig.1 (1).

High-priced diamond and cubic boron nitride are used mainly as coatings or thin wafers brazed on carbides or ceramics in drilling and cutting applications.

Ceramics are used in substantial amounts in the minerals industry as pipe and chute linings where both the stress and the impact are low. Their general applications are shown in Table 9 (1).

Refractory carbides, mainly tungsten carbides, are used mainly in the mining industry as drilling and boring tools in the insert form.

METALS (IRONS AND STEELS)

The major metallic materials used in wear resistant applications and their general characteristics are listed in Table 10. Their mechanical properties are listed in Table 11 (1). The wear behaviour of these materials is affected by alloy type, composition, grade, carbon content, carbide volume fraction and matrix structure. Detailed information is available from the references (5-13).

PLASTICS

Plastics are used successfully in high-stress abrasion under moderate impact, in low-stress abrasion, and combined erosion and corrosion. Plastics are not suitable for use under severe impact, gouging abrasion and elevated temperature. Their mechanical properties are listed in Table 12 (1). Rubbers with their resilience are used as liners for slurry pipelines, mills, chutes and truck bodies under moderate impact. Polyurethanes with their superior mechanical properties at higher hardness (85-95A durometer are used in slurry pump components, screen decks, flotation impellers and hydrocyclone components. Ultra-high molecular weight (UHMW) polyethylenes (2.0-7.0 million molecular weight) with low frictional coefficients and resistance to corrosion, low stress and impact are used as storage bins, chute liners and liners for excavation equipment. UHMW polyethylene is not suitable for use where severe cutting is anticipated such as handling of coarse, high-density, angular abrasive materials.

DISCUSSION

The prospect to develop wear-resistant materials in Canada is tremendous as we are a rich resource producing country. Yet most mining and mineral equipment is imported. This includes many wear-resistant materials. At CANMET/MTL wear-resistant materials research has been tackled in different fields:

- CANMETCOAT was developed to increase the life of digger teeth;
- ADI grinding balls for mineral dressing and ADI materials for disc cutter and agriculture tillage tool are under development;
- Hard facing technology has been undertaken to extend equipment and tool life;

- Abrasive wear testing has been done to evaluate wear materials and to correlate wear resistance with microstructure;
- Cryogenic treatment to investigate the effect of distribution of retained austenite, primary and secondary carbides on wear resistance.

Cryogenic treatment seems to have potential in increasing wear resistance without changing other mechanical properties. Basically it reduces the amount of retained austenite and transforms it into martensite and also some fine carbide or carbon clusters. The advantages could be stabilized retained austenite with lower Md (stress induces martensitic transformation temperature) which will not undergo stress-induced transformation. Since there is tensile stress generated during austenite-martensite transformation, a lower Md will help to eliminate the source of internal tensile stress, hence maintain the ductility of the retained austenite. This in turn will reduce crack initiation and crack propagation. Martensite and carbide formed during cryogenic treatment will be stress relieved during warming up and subsequent temper treatment if it is required.

Further research is required to correlate microstructure: i.e., size, distribution and type of carbides; type and distribution of martensite, amount of retained austenite and Md temperature, grain size, amount and size of primary carbide versus wear resistance. The information generated is not limited to modifying existing wear components but also can be used in developing new wear-resistant materials include tonnage plates, ADI and tool steels.

SUMMARY

Wear materials used in the mining and minerals industry are briefly introduced. More detailed information can be found in the references. Projects at CANMET/MTL are described and cryogenic treatment will be further studied to improve the wear resistance of existing materials and also as a basis for developing new materials.

REFERENCES

1. Mutton, P.J. Abrasion resistant materials for the Australian minerals industry. Vol.1 Materials selection handbook, 1988.

2. MacDonald, A.M., Mutton, P.J. and Sinclair, W.J. Abrasion resistant materials for the Australian minerals industry. Vol.2 Applications for advanced ceramics, 1988.

3. Czichos, H., Systems analysis and description of wear processes, Symposium on Metallurgical Aspect of Wear, 1981.

4. ASM Metals Handbook, 9th ed., Vol. 16 Machining, 1989.

5. Materials selection for the minerals industry: A short course sponsored by the TMS-AIME continuing education committee, 1977.

6. Barr, R.Q., Materials for the mining industry, Symposium sponsored by Climax Molybdenum Co., Vail, Colorado, 1974.

7. Gillins, L., Wear in slurry pipelines, BHRA information series No.1, BHRA Fluid engineering, UK, 1980.

8. Landsdown, A.R. and Price, A.L., Materials to resist wear, A guide to their selection and use, Pergamon press, 1986.

9. Sarkar, A.D., Wear of metals, Pergamon Press, 1976.

10. Lipson, C and Colwell, L.V., Handbook of mechanical wear, University of Michigan Press, 1961.

11. Rigney, D.A., Fundamentals of friction and wear of materials, ASM, 1981.

12. Rigney, D.A. and Glaeser, W.A., Source book on wear control technology, ASM, 1978.

13. Peterson, M. and Winer, W, Wear control handbook, ASME, 1976.

Table 1. Wear components in the mining and mineral processing equipment.

OPERATION	EQUIPMENT	WEAR COMPONENTS
Mining	Shovels, Draglines, Front End Loaders	Buckets, Teeth, Adaptors
	Trucks, Scrapers	Trays, Blades
Crushing	Jaw, Cone and Gyratory Crushers	Jaws, Mantles, Concaves, Bowls, Liners
	Impact Crushers	Hammers, Blow Bars.
Screening	Grizzlies, Screens, Trommels	Screen Decks, Underpans Discharge Lips
Conveying/Handling	Conveyors, Chutes, Pipes, Launders	Liners, Impact Curtains, Bends
Grinding	Semi-autogenous Mills Rod Mills Ball Mills	Balls, Rods, Liners, Grates, Feed Chutes, Discharge Trommels
Pumping	Slurry Pumps	Impellers, Volute and Frame Plate Liners
Classification	Cyclones, Spirals	Hoods, Vortex Finders, Bodies, Spigots
Separation	Flotation Cells, Magnetic Separators	Agitators, Drums

Table 2. Selection of materials for wear.

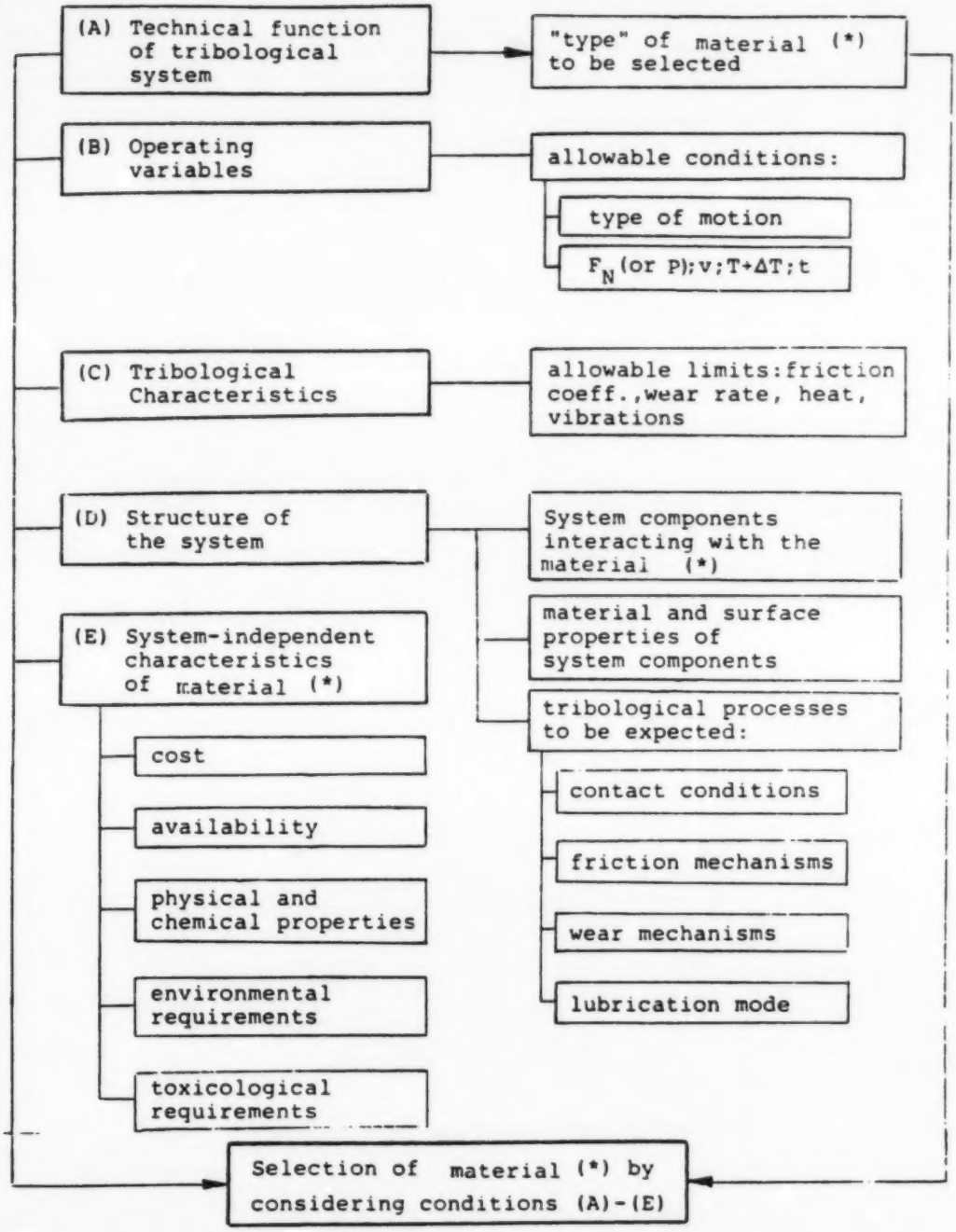
(A) Technical function of tribological system
"type" of material (*) to be selected
(B) Operating variables
allowable conditions:
type of motion
F_N (or P); v; T+ΔT; t
(C) Tribological Characteristics
allowable limits: friction coeff., wear rate, heat, vibrations
(D) Structure of the system
System components interacting with the material (*)
material and surface properties of system components
tribological processes to be expected:
contact conditions
friction mechanisms
wear mechanisms
lubrication mode
(E) System-independent characteristics of material (*)
cost
availability
physical and chemical properties
environmental requirements
toxicological requirements
Selection of material (*) by considering conditions (A)-(E)

Table 3. System description of wear.

wear = f (operating variables; systems structure)

symbolically:

$w = f(\{X\};\ S = \{A, P, R\})$

where

$\{X\}$: set of the operating variables, consisting of

- type of motion
- load F_N
- velocity v
- temperature T
- operating duration t

$S = \{A, P, R\}$: structure of the system, consisting of

- $\{A\}$ elements of the system
- $\{P\}$ properties of the elements
- $\{R\}$ interactions between elements

Table 4. Factors affecting abrasive wear.

ABRASIVE MATERIAL	CONTACT CONDITIONS	WEAR MATERIAL
particle size	force/impact level	hardness
particle shape	velocity	yield strength
hardness	impact/impingement angle	elastic modulus
yield strength	sliding/rolling	ductility
fracture properties	temperature	toughness
concentration	wet/dry	work-hardening characteristics
	pH	fracture toughness
		microstructure
		corrosion resistance

Table 5. Mechanical, physical, and thermal properties of PCD, PCBN, and other tool materials.

Tool material	Density kg/m³	Density lb/ft³	Compressive strength GPa	Compressive strength psi × 10⁶	Fracture toughness MPa√m	Fracture toughness ksi√in.	Knoop hardness GPa	Knoop hardness psi × 10⁶
Al_2O_3	3.91	0.244	4.00	0.580	2.33	2.12	16	2.3
Al_2O_3 + TiC	4.28	0.267	4.50	0.653	3.31	3.01	17	2.5
Sialon	3.20	0.200	3.50	0.508	5.00	4.55	13	1.9
Tungsten carbide (K10)	14.70	0.918	4.50	0.653	10.80	9.83	13	1.9
PCBN(a) (Amborite)	3.12	0.195	3.80	0.551	6.30	5.73	28	4.1
PCD(b) (Syndax3)	3.43	0.214	4.74	0.687	6.89	6.27	50	7.3
PCD(c) (Syndite 010)	4.12	0.257	7.60	1.102	8.80	8.01	50	7.3
Single-crystal diamond	3.52	0.220	8.58	1.244	3.40	3.09	57–104	8.2–15.1
PCBN(d) (DBC50)	4.28	0.267	3.55	0.515	3.70	3.37	28	4.1

Tool Material	Young's modulus GPa	Young's modulus psi × 10⁶	Modulus of rigidity GPa	Modulus of rigidity psi × 10⁶	Bulk modulus GPa	Bulk modulus psi × 10⁶	Poisson's ratio, ν	Coefficient of thermal expansion, 10⁻⁶/K	Thermal conductivity W/m · K	Thermal conductivity Btu/ft · h · °F
Al_2O_3	380	55	153	22.2	243	35.2	0.24	8.50	22.7	13.1
Al_2O_3 + TiC	370	54	160	23.2	232	33.6	0.22	7.80	16.7	9.65
Sialon	300	44	117	16.9	227	32.9	0.28	3.20	20–25	12–14
Tungsten carbide (K10)	620	90	258	37.4	375	54.4	0.22	5.00	100	58
PCBN(a) (Amborite)	680	99	279	40.4	405	58.7	0.22	4.90	100	58
PCD(b) (Syndax3)	925	134	426	61.8	372	54.0	0.086	3.80	120	69
PCD(c) (Syndite 010)	776	112	363	52.6	301	43.7	0.07	4.20	560	323
Single-crystal diamond	1141	165	553	80.2	442	64.1	0.07	1.50–4.80	500–2000(e)	290–1160(b)
PCBN(d) (DBC50)	587	85	284	41.2	254	36.8	0.15	4.70	44	25

(a) Solid PCBN. (b) Solid, thermally stable PCD used mainly in mining applications. (c) Layered PCD. (d) Layered PCD with lowered CBN content. (e) Depending on crystal orientation and perfection

Table 6. Properties of refractory metal carbides.

Carbide	Hardness, HV (50 kg)	Crystal structure	Melting point °C	Melting point °F	Theoretical density, g/cm³	Modulus of elasticity GPa	Modulus of elasticity psi × 10⁶	Coefficient of thermal expansion, μm/m · K
TiC	3000	Cubic	3100	5600	4.94	451	65.4	7.7
VC	2900	Cubic	2700	4900	5.71	422	61.2	7.2
HfC	2600	Cubic	3900	7050	12.76	352	51.1	6.6
ZrC	2700	Cubic	3400	6150	6.56	348	50.5	6.7
NbC	2000	Cubic	3600	6500	7.80	338	49.0	6.7
Cr_3C_2	1400	Orthorhombic	1800(a)	3250	6.66	373	54.1	10.3
WC	(0001) 2200 (10$\bar{1}$0) 1300	Hexagonal	~2800(a)	5050	15.7	696	101	(0001) 5.2 (10$\bar{1}$0) 7.3
Mo_2C	1500	Hexagonal	2500	4550	9.18	533	77.3	7.8
TaC	1800	Cubic	3800	6850	14.50	285	41.3	6.3

(a) Not congruently melting, dissociation temperature. Source: Ref 8

Table 7 Properties of representative cobalt-bonded cemented carbides

Nominal composition	Grain size	Hardness, HRA	Density g/cm³	Density oz/in.³	Transverse strength MPa	Transverse strength ksi	Compressive strength MPa	Compressive strength ksi	Modulus of elasticity GPa	Modulus of elasticity psi × 10⁶	Relative abrasion resistance(a)	Coefficient of thermal expansion, μm/m · K at 200 °C (390 °F)	Coefficient of thermal expansion, μm/m · K at 1000 °C (1830 °F)	Thermal conductivity W/m · K
97WC-3Co	Medium	92.5–93.2	15.3	8.85	1590	230	5860	850	641	93	100	4.0	. . .	121
94WC-6Co	Fine	92.5–93.1	15.0	8.67	1790	260	5930	860	614	89	100	4.3	5.9	. . .
	Medium	91.7–92.2	15.0	8.67	2000	290	5450	790	648	94	58	4.3	5.4	100
	Coarse	90.5–91.5	15.0	8.67	2210	320	5170	750	641	93	25	4.3	5.6	121
90WC-10Co	Fine	90.7–91.3	14.6	8.44	3100	450	5170	750	620	90	22	. . .	. . .	. . .
	Coarse	87.4–88.2	14.5	8.38	2760	400	4000	580	552	80	7	5.2	. . .	112
84WC-16Co	Fine	89	13.9	8.04	3380	490	4070	590	524	76	5	. . .	. . .	. . .
	Coarse	86.0–87.5	13.9	8.04	2900	420	3860	560	524	76	5	5.8	7.0	88
75WC-25Co	Medium	83–85	13.0	7.52	2550	370	3100	450	483	70	3	6.3	. . .	71
71WC-12.5TiC-12TaC-4.5Co	Medium	92.1–92.8	12.0	6.94	1380	200	5790	840	565	82	11	5.2	6.5	35
72WC-8TiC-11.5TaC-8.5Co	Medium	90.7–91.5	12.6	7.29	1720	250	5170	750	558	81	13	5.8	6.8	50

(a) Based on a value of 100 for the most abrasion-resistant material

Table 8 Mechanical properties of ceramic materials

MATERIAL	HARDNESS (HV)	ELASTIC MODULUS (GPa)	FRACTURE TOUGHNESS (MPa√m)
Basalt	700- 800	100	1-2
Alumina	1800-2300	380	3
Transformation toughened Alumina	1600	370	5-9
Partially-stabilised Zirconia	1020-1120	205	8-15
Silicon Carbide	2500	400	5
Silicon Nitride	1800	310	5-6
Silicon-Nitride Bonded Silicon Carbide	2000	120	–

Table 9 Present applications for ceramics in the minerals industry

APPLICATION	MATERIAL
Chute linings	Alumina, Basalt
Pipe linings	Basalt
Hydrocyclone linings	Fused Zirconia/Alumina (ZAC), Alumina, Silicon Nitride-Bonded Silicon Carbide
Pump components	Fused Zirconia/Alumina
Spray nozzles (spray dryer)	Silicon Carbide
Orifice plates	PSZ, Alumina
Dry bearings	PSZ

Table 10. Summary of abrasion resistant alloys.

ALLOY TYPE	GENERAL CHARACTERISTICS	TYPICAL APPLICATIONS
Austenitic Manganese Steels	High work hardening characteristics, resistant to heavy and repeated impact, gouging abrasion.	Jaw and gyratory crushers
Low Alloy Steels:		
• Cast Martensitic	High yield strength; impact toughness and abrasion resistance determined by heat treatment.	Bucket components (teeth, adaptors, etc.)
• Wrought Martensitic	Weldable, moderate abrasion resistance.	Wearplate (chutes, truck trays, etc.)
• Cast Pearlitic	High ductility, moderate abrasion resistance.	Mill liners
Alloy White Irons • Nickel-Chromium • Chromium-Molybdenum • High Chromium	High abrasion resistance low impact resistance	Pump components, wear liners, mill liners
Chromium Carbide Hardfacing	High abrasion resistance, moderate impact resistance.	Wear liners, slurry pipelines

Table 11. Mechanical properties of abrasion resistant alloys.

COMPARATIVE MECHANICAL PROPERTIES OF ABRASION RESISTANT FERROUS ALLOYS

MATERIAL	HARDNESS (HB)	IMPACT TOUGHNESS (J)
Austenitic Mn steel		
• Standard (11-14% Mn)	200-250	140
• Lean Alloy (6% Mn)	200-250	30
Low Alloy Steels		
• Cast Martensitic	400-600	15-25
• Wrought Martensitic	300-550	20-70
• Cast Pearlitic	250-420	5-10
Alloy White Irons	600-900	2-5

Table 12. Mechanical properties of plastic abrasion-resistant materials.

TYPE	HARDNESS (DUROMETER)	ELASTIC MODULUS (MPa)	TENSILE STRENGTH AT BREAK (MPa)	ELONGATION AT BREAK (%)
Rubbers-natural and synthetic	45-75A	0.7-3.5	10-20	700-900
Polyurethanes	60A-60D	14-20	20-60	300-500
UHMW Polyethylenes	60-70D	40	10-40	400-600

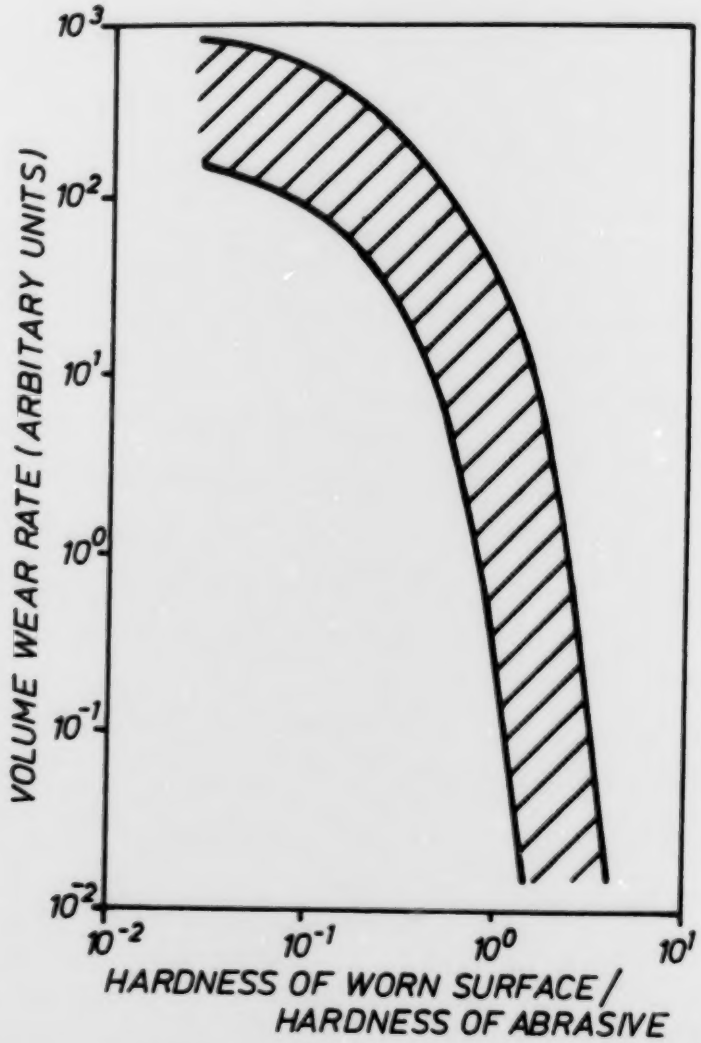

Fig.1 Effect of abrasive hardness on wear behaviour of metals and ceramics